Challenges for Electronics in the Vision for Space Exploration*

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** Radiation effects are the prime consideration in this talk. Reliability must ALSO be considered.*

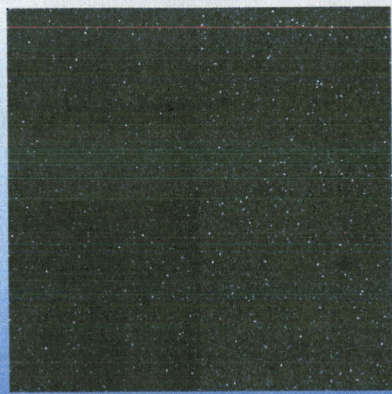
Outline

- Background – Radiation Effects on Electronics
- Uniqueness of Exploration Systems Missions
  - Types of missions
  - Comparison to traditional missions
- Electronic Parts and Exploration
  - Sample Electronics Radiation and Reliability Issues that Impact Space Exploration
- Four-pronged Infrastructure Approach
  - Parts Management Process
  - Parts Reliability Capability
  - Radiation Effects Knowledge and Capabilities
  - Exploration-specific Technology Evaluation
- Recommended Investment Areas
- Summary Comments

Presented by Kenneth LaBel at the Solar and Space Physics for the Vision for Space Exploration (SSPVSE), Charlottesville, Virginia, Oct. 16-20, 2005.

Radiation Effects and Spacecraft

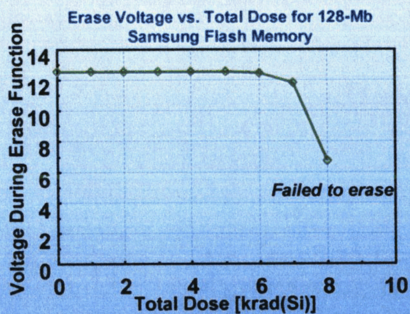
- **Critical areas for design in the natural space radiation environment**
  - **Long-term effects causing parametric and /or functional failures**
    - **Total ionizing dose (TID)**
    - **Displacement damage**
  - **Transient or single particle effects (Single event effects or SEE)**
    - **Soft or hard errors caused by proton (through nuclear interactions) or heavy ion (direct deposition) passing through the semiconductor material and depositing energy**



An Active Pixel Sensor (APS) imager under irradiation with heavy ions at Texas A&M University Cyclotron

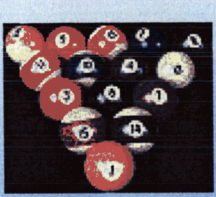
Total Ionizing Dose (TID)

- **Cumulative long term *ionizing* damage due to protons & electrons**
  - **keV to MeV range**
- **Electronic Effects**
  - **Threshold Shifts**
  - **Leakage Current**
  - **Timing Changes**
  - **Functional Failures**
- **Unit of interest is krads(material)**
- **Can *partially* mitigate with shielding**
  - **Reduces low energy protons and electrons**



Displacement Damage (DD)

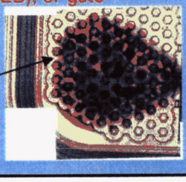
- Cumulative long term *non-ionizing* damage due to protons, electrons, and neutrons
  - keV to MeV range
- Electronic Effects
  - Production of defects which results in device degradation
  - May be similar to TID effects
  - Optocouplers, solar cells, charge coupled devices (CCDs), linear bipolar devices
    - Lesser issue for digital CMOS
- Unit of interest is particle fluence for each energy mapped to test energy
  - Non-ionizing energy loss (NIEL) is one means of discussing
- Can *partially* mitigate with shielding
  - Reduces low energy protons and electrons



Single Event Effects (SEEs)

- An SEE is caused by a ***single charged particle*** as it passes through a semiconductor material
  - Heavy ions (cosmic rays and solar)
    - Direct ionization
  - Protons(trapped and solar)/neutrons (secondary or nuclear) for sensitive devices
    - Nuclear reactions for electronics
    - Optical systems, etc are sensitive to direct ionization
- Unit of interest: linear energy transfer (LET). The amount of energy deposited/lost as a particle passes through a material.
- Effects on electronics
  - If the LET of the particle (or reaction) is greater than the amount of energy or critical charge required, an effect may be seen
    - Soft errors such as upsets (SEUs) or transients (SETs), or
    - Hard (destructive) errors such as latchup (SEL), burnout (SEB), or gate rupture (SEGR)
- Severity of effect is dependent on
  - type of effect
  - system criticality

Destructive event in a COTS 120V DC-DC Converter



Uniqueness of Exploration Systems Missions

- **The Vision for Space Exploration creates a new paradigm for NASA missions**
  - **Transport (Crew Exploration Vehicle – CEV), and**
  - **Lunar and Mars Exploration and Human Presence**
- **If one considers the additional hazards faced by these concepts versus more traditional NASA missions, multiple challenges surface for reliable utilization of electronic parts.**
  - **The true challenge is to provide a risk as low as reasonably achievable (ALARA – a traditional biological radiation exposure term), while still providing cost effective solutions.**
- **The following chart tabulates the exploration environmental challenges for electronic parts relative to traditional NASA missions.**

Summary of Environment Hazards for Electronic Parts in NASA Missions

	Plasma (charging)	Trapped Protons	Trapped Electrons	Solar Particles	Cosmic Rays	Human Presence	Long Lifetime (>10 years)	Nuclear Exposure	Repeated Launch	Extreme Temperature	Planetary Contaminates (Dust, etc)
GEO	Yes	No	Severe	Yes	Yes	No	Yes	No	No	No	No
LEO (low-incl)	No	Yes	Moderate	No	No	No	Not usual	No	No	No	No
LEO Polar	No	Yes	Moderate	Yes	Yes	No	Not usual	No	No	No	No
Shuttle	No	Yes	Moderate	No	No	Yes	Yes	No	Yes	Rocket Motors	No
ISS	No	Yes	Moderate	Yes - partial	Minimal	Yes	Yes	No	No	No	No
Interplanetary	During phasing orbits; Possible Other Planet	During phasing orbits; Possible Other Planet	During phasing orbits; Possible Other Planet	Yes	Yes	No	Yes	Maybe	No	Yes	Maybe
Exploration - CEV	Phasing orbits	During phasing orbits	During phasing orbits	Yes	Yes	Yes	Yes	No	Yes	Rocket Motors	No
Exploration – Lunar, Mars	Phasing orbits	During phasing orbits	During phasing orbits	Yes	Yes	Yes	Yes	Maybe	No	Yes	Yes

Yellow indicates significant Exploration hazards

Discussion of the Hazard for Electronic Parts and Exploration

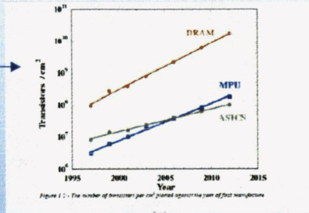
- As can be observed from the previous chart, Exploration Systems faces a unique electronic parts challenge not only for radiation exposure, but for reliability challenges as well.
  - Harsher environment than recent human presence missions (ISS, Shuttle)
  - Potentially, the combined hazard of traditional earth science (LEO) and space science (interplanetary) missions
- Cost effectiveness may drive use of innovative commercial electronics usage to meet performance constraints
  - Is this unique to Exploration? No, but with the hazard faced, one must be careful to plan for radiation and electronic parts reliability

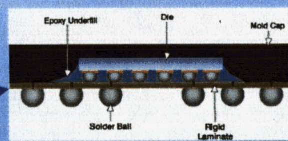
Types of Electronic Parts for Exploration

- One may view electronic parts for Exploration as meeting needs in three categories
  - Standard electronics
    - E.g., capacitors
      - Basic components
  - Standard building blocks
    - E.g., Field Programmable Gate Arrays (FPGAs)
      - Widespread usage in most systems
  - Custom devices not available as "off-the-shelf"
    - E.g., nuclear power or EVA
      - Needed for a specific application
- Note: Commercial-of-the-shelf (COTS) assemblies (e.g., commercial electronic cards or instruments) also may be considered
  - Screening is more complicated than with ISS in this approach due to more extreme environment faced
- In any case, coordination of the parts needs and parts management can be daunting for such a program
  - Infrastructure required to provide a cost-effective basis for electronic parts for Exploration

A Critical Juncture for Space Usage – Commercial Changes in the Electronics World

- Over the past decade plus, much has changed in the semiconductor world. Among the rapid changes are:
  - Scaling of technology
    - Increased gate/cell density per unit area (as well as power and thermal densities)
    - Changes in power supply and logic voltages (<1V)
      - Reduced electrical margins within a single IC
    - Increased device complexity, # of gates, and hidden features
    - Speeds to >> GHz (CMOS, SiGe, InP…)
  - Changes in materials
    - Use of antifuse structures, phase-change materials, alternative K dielectrics, Cu interconnects (previous – Al), insulating substrates, ultra-thin oxides, etc…
  - Increased input/output (I/O) in packaging
    - Use of flip-chip, area array packages, etc
  - Increased importance of application specific usage to reliability/radiation performance





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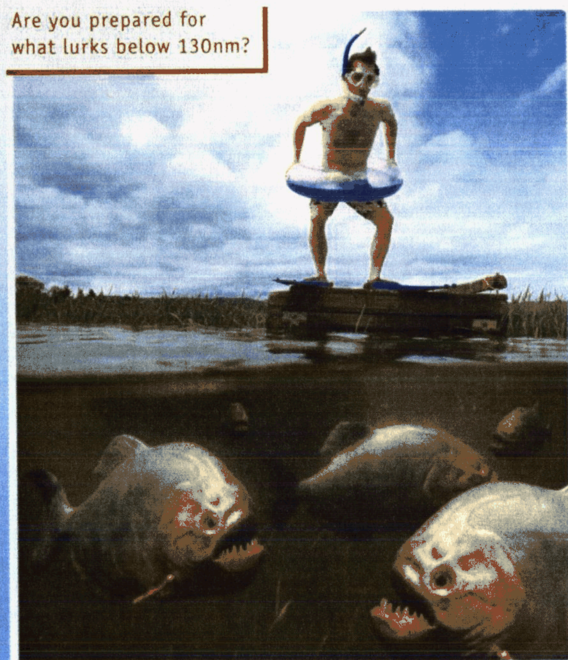

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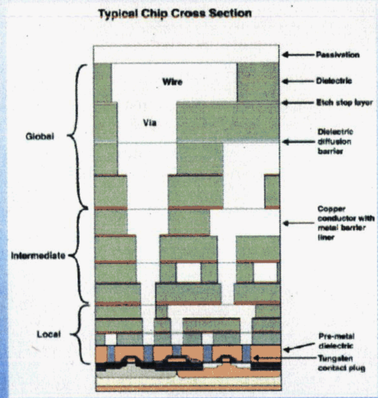
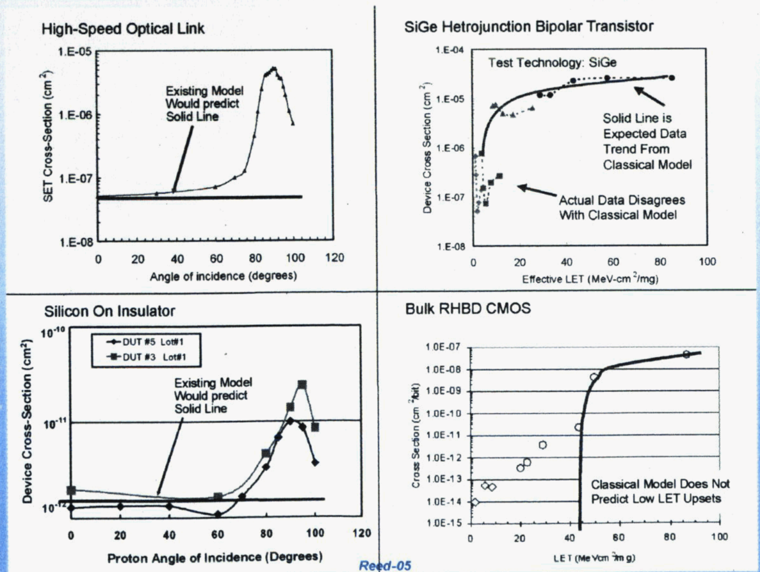
Implications for Electronics in Space

- **With all these changes in the semiconductor world, what are the implications for usage in space? Implications for test, usage, qualification and more**
  - **Speed, power, thermal, packaging, geometry, materials, and fault/failure isolation are just a few for emerging challenges for radiation test and modeling.**
    - **Reliability challenges are equally as great**
  - **The following chart (courtesy of Vanderbilt University) looks at some of the recent examples of test data that imply shortfalls in existing radiation performance models.**
    - **Technology assumptions in tools such as CREME96 are no longer valid**



Sample Modeling Shortfalls



Current Status of Radiation Knowledge Maturity for Electronics

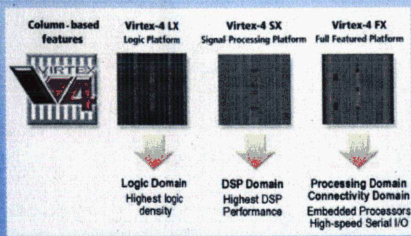
Radiation Response	Guideline Document	Test Method	Data Base	Modeling & Simulation
SEU/MBU	Yes	Yes	Yes	~ mature
SET	No	No	No	No
SEL	Yes	Yes	Yes	No
SEGR	No	No	No	No
SEFI	No	No	No	No
TID	Yes	Yes	Yes	Yes
Displacement Damage	Yes	Yes	No	No

Approach to Electronic Parts Assurance for Exploration

- **What follows is a recommended four-prong approach alliances to existing programs**
  - **The main alliance is with the NASA Electronic Parts and Packaging (NEPP) Program (OSMA) that provides limited ground-based technology evaluation and Parts Assurance on a "One NASA" basis.**
    - **NEPP works generic technology issues that are NOT specific to a Program, but of general NASA interest**
      - **Note: NEPP budget is ~ ½ of FY2000 levels due to cuts and full-cost implementation**
      - **What is being recommended is complementary to NEPP**
  - **Other alliances with flight testbeds such as LWS SET and New Millenium are also encouraged**
  - **The four prongs for electronic parts assurance are**
    - **Parts management and control**
    - **Reliability test and analysis capability**
    - **Radiation effects test and analysis capability**
    - **Exploration-specific technology evaluation**
- ***Environment models are outside of traditional parts assurance, but recommendations will be made later in presentation***

Parts Management and Control

- **Support coordination, management, and control of electronic parts as related to Exploration Missions**
- **Support infrastructure issues required for successful electronic parts utilization**
  - **Vendor audits, standards committees, etc**
- **Recommendation**
  - **Provide parts support at each center (min. 1 FTE/WYE per)**



Complex new FPGA architectures include hard-cores: processing, high-speed I/O, DSPs, programmable logic, and configuration latches

Reliability Test and Analysis

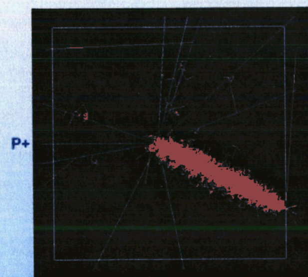
- **Goal: Provide dedicated infrastructure to support new and existing device evaluation**
  - **Provide a quick-turn capability for performing failure analyses on technologies of interest to Exploration**
  - **Keep evaluation capabilities on par with commercial technology advances**
    - **Allows cost-effective evaluation of space-specific issues**
    - **Keeps labs "state-of-the-art"**
- **Recommendation**
  - **Utilize existing strengths at GSFC, JPL, GRC, MSFC, ARC, LaRC, and JSC. Examples,**
    - **GSFC and JPL are MAIN strengths for parts reliability efforts for the agency**
    - **GRC has capability for extreme temp, power, and RF**
    - **MSFC and JSC have historical base for electronics for human presence missions**
- ***Note: the cost for the capability to evaluate "state of the art" is on a rapid upwards spiral. Test equipment for state-of-the-art can run $Ms!***

Radiation Effects Test and Analysis

- Goal: Provide dedicated infrastructure to support new and existing device evaluation for radiation specific issues
  - Provide a quick-turn capability for gathering radiation knowledge on technologies of interest to Exploration
  - Keep evaluation capabilities on par with commercial technology advances
    - Allows cost-effective evaluation of space-specific issues
    - Keeps labs "state-of-the-art"
  - Provide a heavy ion test capability on par with that developed for protons at IU for ISS for device evaluation
- Recommendation
  - Utilize existing strengths at GSFC, JPL, and JSC
    - GSFC and JPL are recognized strengths for radiation effects for the agency (and the aerospace industry)
    - JSC has historical base for human presence coupled with electronics
  - Support high energy heavy ion test facility at MSU for commercial device/assembly evaluation
    - Includes purchase of time for Exploration technologies evaluations

Evaluation of Technologies Specific to Exploration

- Goal: Provide evaluation of technologies of specific interest to Exploration
  - High and cold temperature
  - Long-life
  - Nuclear exposure, etc.
- Recommendation
  - Utilize strengths at GSFC, JPL, GRC, MSFC, LaRC, ARC, and JSC
    - GSFC and JPL have traditional "One NASA" experience for electronic parts reliability leadership



Sample 100 MeV proton reaction in a 5 um Si block.
Reactions have a range of types of secondaries and LETs.
(after Weller, 2004)

Electronics and Radiation Environment Investment Areas

- Understanding extreme value statistics as it applies to radiation particle impacts
  - Small probability risk analysis (if 1 in 1e9 particles can cause an effect, how do we test, model, and interpret for system risk?)
- System Radiation Risk Tools
  - Interpreting device effects at the system level
- High-Energy SEU Microbeam Two-Photon Absorption Laser
  - Ability to determine fault cause in modern devices
- Portable High-Speed Device Testers
  - Required to provide a cost-effective meaningful answer
- Physics Based Modeling Tool
  - Provide an answer to shortfalls in tools such as CREME96
- Radiation hardening of devices
  - Development of substrate engineering processing methods to decrease charge generation and enhance recombination in CMOS
  - Improved radiation hardening of sensors/detectors
- Improved solar heavy ion model
  - System risk analysis requires this
- Update to AE-8 and AP-8
  - Important to CEV and phasing orbits
- Standard radiation environment "engineering-grade" sensor for all missions for long-term technology performance tracking and anomaly resolution. Commensurate technology database.

Summary

- This presentation has been a brief snapshot discussing electronics and Exploration-related challenges.
  - Radiation effects have been the prime target, however, electronic parts reliability issues must also be considered.
    - Modern electronics are designed with a 3-5 year lifetime typical.
      - "Upscreening" does not improve reliability, merely determine inherent levels.
- To cope with the uniqueness of the Exploration missions' hazard, a program infrastructure and commensurate targeted research are suggested.